10/561724
IAP20 Rec'd PCT/PTO 20 DEC 2005

[10191/4458]

METHOD FOR PREDICTING THE REMAINING LIFETIME OF AN ELECTRIC ENERGY STORAGE MECHANISM

The present invention relates to a method for predicting the remaining lifetime of an electric energy storage mechanism according to the preamble of the main claim as well as devices for implementing the methods according to the present invention.

Background Information

With electric energy storage mechanisms such as batteries, it is extremely important to predict the remaining lifetime until they become unusable, in particular in the case of lead batteries in motor vehicles. The battery may be replaced promptly due to a warning to the operator of the vehicle before an imminent battery failure, thereby preventing breakdown of a vehicle or failure of electric devices in the vehicle, in particular those critical for safety, such as x-by-wire systems. However, replacement of batteries too early must be avoided for cost reasons. Therefore, metrics tailored for the particular application and analyzable as accurately as possible are crucial for the useful life of a battery having parameterizable threshold values for a battery replacement display.

Various methods of determining the useful life (SOH = state of health) of energy storage mechanisms, in particular lead batteries such as those used in the automotive field, are known from the literature. One measure used for the state of aging of a battery is the decline in storage capacity in comparison with the new state, which is estimated, e.g., by monitoring such operating conditions as charge conversion, exhaustive battery discharge phases and ambient temperature (US 6,103,408) or from the current and voltage curves in typical recurring load cases (engine start). In addition, the decline in efficiency is used as a measure of aging by observing the voltage dip when starting the engine (DE 19750309A) or the temperature- and charge state-compensated dynamic internal resistance (DE 3712629C2, DE 10049495A) over the lifetime of a battery.

The prevailing state of health of the energy storage mechanism is thus evaluated either on the basis of the prevailing storage capacity or the efficiency based on engine startup. The literature does not describe or analyze any more detailed criteria for the state of health applicable to different applications including combined applications (engine start, electric or

hybrid vehicle, power supply to safety-critical electric consumers, ...). Nor is there any prediction of the remaining lifetime.

Object of the Invention

By extrapolation with the help of a mathematical model of the energy storage mechanism, in particular an automotive lead battery (e.g., DE 10301823, DE 10303506), the present invention determines the remaining lifetime until the levels drop below any preselectable minimum efficiency and/or storage capacity under given boundary conditions for the charge state and temperature. The remaining lifetime and a warning when the battery falls below a preselected threshold are displayed for the driver of the vehicle.

Advantages of the Invention

The present invention overcomes the disadvantages of the known methods for determining the state of health of an energy storage mechanism as described in the related art; this is accomplished with the help of a model of the energy storage mechanism, the parameters being adapted continuously to the real values over the lifetime of the device. The anticipated remaining lifetime is determined by extrapolation from the values that are calculated at regular intervals on the basis of the model and stored, i.e., the values for the efficiency and/or storage capacity based on a preselected charge stage (e.g., full charge) and temperature (e.g., cold start temperature -18°C) and the minimum values required for the particular application.

The advantages in comparison with the related art include the following in particular:

– Use of a mathematical model having automatic adaptation to the energy storage mechanism used by continuous adaptation of the parameters of the energy storage model (e.g., important after changing a battery in a vehicle → no engine characteristic maps are required for the aging behavior of the battery used) → more accurate determination of the state of health and remaining lifetime → reduced risk of replacing the battery too early or too late;

– Easily parameterizable metrics tailored to the particular application for the state of health of the energy storage mechanism with regard to the storage capacity and/or efficiency → easily applicable to different applications;

– Determination of the remaining lifetime by extrapolation of the time curves of the

calculated storage capacity and/or efficiency based on a certain charge state and temperature → prompt warning with a rapid drop in storage capacity and/or efficiency, although their absolute values are currently still sufficiently high

→ e.g., a battery no longer capable of a cold start under winter conditions is detected in the summer and may thus be replaced promptly.

Description/Implementation

Figure 1 shows the basic structure of the method. It is divided into three steps. First, in the first step the parameters of the mathematical energy storage mechanism model summarized by vector $\underline{p}$ are adapted by a parameter estimator (e.g., Kalman filter according to R.304628) by continuous measurement of the operating parameters, i.e., battery current I_{Batt}, battery voltage U_{Batt} and battery temperature T_{Batt}. In the case of a lead battery $\underline{p}$ includes parameters such as internal ohmic resistance, capacitance and diffusion resistance, for example. It is important that these parameters are standardized to a predetermined temperature (e.g., 25°C) and charge state (full charge), i.e., with a given battery they change only as a result of aging factors.

In the second step, the mathematical battery model used in the voltage and charge predictor is initialized with battery parameters $\underline{p}$. The voltage predictor supplies the prevailing efficiency of the battery by predicting, with the help of the battery model, voltage responses $U_{Batt,pred1,2,...}$ to specified load current profiles $I_{BattU1,2,...}$ under given boundary conditions for battery variables of state $\underline{z}_{U1,2,...}$ and temperature $T_{BattU1,2,...}$ (see DE 10301823). Vector $\underline{z}_{U1,2,...}$ of the battery parameters of state to be specified of the battery model contains in the case of a lead battery, e.g., parameters such as open-circuit voltage, concentration and breakdown polarization. $I_{BattU1,2,...}$, $\underline{z}_{U1,2,...}$ and $T_{BattU1,2,...}$ are to be specified as a function of the application of the energy storage mechanism. For example, in the case of a starter battery for I_{BattU} the current profile required by the starter at a cold start temperature of $T_{BattU} = -18°C$ would be a reasonable specification with $\underline{z}_{U}$ corresponding to a fully charged battery.

The charge predictor supplies the prevailing storage capacity of the battery by using the battery model to calculate usable charges $Q_{e,pred1,2,...}$ for discharge currents $I_{BattQe1,2,...}$ and temperatures $T_{BattQe1,2,...}$ starting from specified battery states $\underline{z}_{Qe1,2,...}$ until the battery voltage falls below specified values $U_{BattQ1,2,...}$ (DE 10301823). For example, when $I_{BattQe} = I20 =$

K20/20 h, $T_{BattQe} = 27°C$, $U_{BattQe} = 10.5$ V, $\underline{z}_{Qe}$ = full charge, the charge predictor indicates the currently usable charge of a starter battery of nominal capacity K20 under nominal conditions.

Using the charge predictor, combined requirements of the energy storage mechanism with regard to storage capacity and efficiency may also be analyzed. To do so, discharge current profile I_{BattQe} is expanded by a load current profile according to those used for predicting voltage and the minimum allowed battery voltage under load with the specific load current profile is used for U_{BattQ} (see DE 10301823). In the case of a starter battery, for example, it is thus possible to calculate the amount of reserve charge at a full charge, a specified discharge current and a temperature up to the startability limit.

In step III, the time characteristics of voltages $U_{Batt,pred1,2,...}$ and usable charges $Q_{e,pred1,2,...}$ calculated by the voltage and charge predictor are stored, and the period of time $t_{remaining}$ until at least one of these parameters drops below its respective specified minimum level $U_{Battmin1,2,...}$ and/or $Q_{emin1,2,...}$ is calculated by extrapolation (see Figure 2). Specified minimum values $U_{Battmin1,2,...}$ and/or $Q_{emin1,2,...}$ characterize the limit until the battery becomes unusable with respect to the particular requirements of its storage capacity and/or efficiency.

In the simplest case the extrapolation may be performed linearly from the last two time-voltage value pairs and/or time-charge value pairs saved at times t_a, t_b:

$$t_{remaining,U} = (t_b - t_a)*(U_{Battmin} - U_{Batt,predb})/(U_{Batt,predb} - U_{Batt,preda})$$

and

$$t_{remaining,Q} = (t_b - t_a)*(Q_{emin} - Q_{e,predb})/(Q_{e,predb} - Q_{e,preda})$$

In the case of multiple specifications for the storage capacity and/or efficiency, resulting remaining lifetime $t_{remaining}$ is determined by forming the minimum of individual values $t_{remaining,U1,2,...}$ and $t_{remaining,Q1,2,...}$:

$$t_{remaining} = \min(t_{temainingU1}, t_{remainingU2}, \ldots, t_{remainingQ1}, t_{remainingQ2}, \ldots) .$$

For more detailed determination of remaining lifetime $t_{remaining}$ the extrapolation may also be performed with more than two time-voltage value pairs and/or time-charge value pairs and more complex methods such as linear regression or in the case of nonlinear curves by using

polynomials or methods based on neural networks (RBF). Furthermore, extrapolation procedures may be derived from curves already measured and thus known for storage capacity and/or efficiency over the lifetime of the battery.

When the remaining lifetime falls below a specified minimum $t_{remaining,min}$, an optical and/or acoustic warning signal is output to the driver, calling for replacement of the battery.

In the case of time curves of the predicted voltage or usable charge having a shallow descent or even a rise and being close to the specified minimum levels, falling below a specified minimum distance between prevailing predicted voltage and/or usable charge and the particular minimum value is supplemented as an additional replacement criterion to avoid a battery replacement warning coming too late:

$$\text{Warning signal} = (t_{remaining} < t_{remaining,min}) \text{ or } \ldots$$

$$(U_{Batt,pred1,2,\ldots} - U_{Battmin1,2,\ldots}) < \Delta U_{Battmin1,2,\ldots} \text{ or } \ldots$$

$$(Q_{e,pred1,2,\ldots} - Q_{emin1,2,\ldots}) < \Delta Q_{emin1,2,\ldots}.$$